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Evaluating the Energy Recovery Potential of Nigerian Coals under Non-Isothermal Thermogravimetry

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Abstract. This study investigated the fuel properties and energy recovery potential of two coal samples from *Ihioma* (IHM) and *Ogboligbo* (OGB) environs in Nigeria. The ultimate, proximate, and bomb calorimetric analyses of the coal were examined. Next, the rank classification and potential application of the coals were evaluated according to the ASTM standard D388. Lastly, thermal decomposition behaviour was examined by non-isothermal thermogravimetry (TG) under pyrolysis conditions from 30 – 900 °C. The results indicated IHM and OGB contain high proportions of combustible elements for potential thermal conversion. The higher heating value (HHV) of IHM was 20.37 MJ/kg whereas OGB was 16.33 MJ/kg. TG analysis revealed 55% weight loss for OGB and 76% for IHM. The residual mass was 23% for IHM and 44% for OGB. Based on the temperature profile characteristics (TPCs); T_{on}, T_{max}, and T_{off}, IHM was more reactive than OGB due to its higher volatile matter (VM). Overall, results revealed the coals are Lignite (Brown) low-rank coals (LRCs) with potential for electric power generation.

1. Introduction

Carbonization (pyrolysis) is one of the oldest and most commonly utilized techniques for converting coal into solid, liquid, and gaseous fuels. It is also a practical approach for fuel synthesis and energy recovery processes. Furthermore, it is an important intermediate reaction in the gasification and combustion of carbonaceous fuels such as biomass and coal.

Coal is the most abundant and widely distributed fossil fuel around the globe. The carbonaceous nature of coal presents significant opportunities for conversion into energy, fuels, and chemicals. Currently, coal utilization plays an important role in the global energy mix, particularly for electricity generation. According to the IEA, global electricity production from coal accounts for 41% or 8,000 TWh although it is projected to rise to 12,000 TWh by 2035 [1]. As a result, coal utilization will significantly contribute to socioeconomic growth and development for the foreseeable future [2]. Furthermore, coal is a widely available, accessible and acceptable source of future energy with potential for poverty alleviation [3]. This is particularly important for energy exploration and exploitation in developing nations like Nigeria with vast new coal deposits [4, 5].

The coal resources in Nigeria are predominantly located in the upper, middle and lower Benue trough which extends from the SW to NE direction across the nation's sedimentary basin [6]. The sedimentary basin spans over 13 states and over 20 localities in the country. Currently, Nigeria's proven resources and reserves amount to 640 million tons and 2.8 billion tons, respectively [5, 6]. This mainly consists of Lignite (12%), Sub-Bituminous (49%) and Bituminous (39%) [7]. Consequently, coal is strategically positioned as an ideal feedstock to address the nation's energy crises [8, 9]. Furthermore, the current low demand for low-rank coals (LRC) like lignite suggests prices may remain low. Hence, the utilization of lignite for electric power generation will potentially result in cheap, reliable, and constant electric power supply in the country.

However, there is limited knowledge on the physicochemical, thermal kinetic, and thermodynamic properties of lignite coal in Nigeria. Previous studies have investigated the geochemistry [10], mineralogical [11], rheological [4], trace element [12], chemical products [13], rank and petrographic [13] properties of Nigerian coals. As a result, the reported findings in the surveyed literature only present insights into the geological, geochemical and mineralogical properties but not the thermochemical fuel properties of lignite coals required for energy recovery in Nigeria. Hence, there is an urgent need to critically examine the essential fuel properties of newly discovered lignite coals as required for application in power generation.

Therefore, the main objective of this study is to examine the physicochemical and thermal fuel properties of coals from *Ihioma* (IHM) and *Ogboligbo* (OGB) environs in Nigeria for potential energy recovery. This will be examined by ultimate, proximate, and bomb calorimetric analyses. Furthermore, the thermal decomposition behavior of the coal samples will be examined by non-isothermal thermogravimetry (TG) under pyrolysis conditions. Lastly, coal rank classification and the potential applications of the coal samples will be evaluated. It is envisioned that the coal properties will assist in the design and development of future energy recovery systems required to boost electric power generation and sustainable development in Nigeria.

2. Experimental

The rock samples of *Ihioma* (IHM) and *Ogboligbo* (OGB) coals from in Imo and Kogi States were acquired from the National Metallurgical Research and Development Centre (NMRDC) in Jos, Nigeria. The samples were subsequently pulverized and sifted using the Retsch™ analytic sieve of mesh size 60 to acquire 250 μm sized particles [14].

Next, the pulverised coals were characterized by elemental, proximate, and bomb calorific analyses. The elemental properties were examined by CHNS analysis using the vario MICRO Cube™ Elemental Analyzer (Germany). The proximate analysis was performed by thermogravimetric analysis (TGA) based on the procedures described in the literature [15].

The calorific (higher heating) value was examined by bomb calorimetry using the IKA C2000 bomb calorimeter (USA) according to the ASTM standard D2015. All tests were repeated twice to ensure the repeatability and reliability of the results. The coal rank classification was estimated based on the ASTM standard D388 as described in the literature [16].

Lastly, the thermal degradation behaviour of the coals was investigated through non-isothermal thermogravimetric (TG) analysis under inert (pyrolysis) conditions. During each run, approximately 15 mg of sample was loaded onto the Perkin Elmer TGA 4000 and heated in an alumina crucible at 10 °C/min from 30 °C to 900 °C. The gaseous species evolved during thermal decomposition were purged by nitrogen gas (N_2) at a flow rate of 50 ml/min. The procedure was aimed at simulating pyrolytic (pyrolysis) decomposition under non-isothermal heating during TGA.

3. Results and Discussion

3.1. Coal Fuel Characteristics

The ultimate, proximate, and bomb calorific analyses of IHM and OGB coals are presented in Table 1. The ultimate analysis is presented in dry ash free (*daf*) basis while the proximate analysis and calorific heating values are presented on dry basis (*db*) for comparison with coal data in the literature [17].

Table 1. Coal Fuel Characteristics

Element	Symbol	IHM Coal	OGB Coal
Carbon	C (wt.% *daf*)	50.49	38.94
Hydrogen	H (wt.% *daf*)	5.74	3.59
Nitrogen	N (wt.% *daf*)	0.71	0.84
Sulphur	S (wt.% *daf*)	1.62	2.37
Oxygen	O (wt.% *daf*)	41.44	54.25
Moisture	MC	4.75	3.12
Volatiles	VM (wt.% *db*)	72.99	53.09
Ash	AC (wt.% *db*)	2.55	1.06
Fixed Carbon	FC (wt.% *db*)	24.46	45.85
Fuel Ratio	FC/VM	0.34	0.86
Higher Heating Value	HHV (MJ/kg)	20.37	16.33
Lower Heating Value	LHV (MJ/kg)	19.20	15.60

The ultimate analysis revealed that IHM and OGB contain sufficient proportions of the combustible fuel elements required for potential energy recovery. As observed, the *C* and *H* content of IHM are significantly higher than OGB coal. Typically, the higher the *C* and *H* content, the higher the calorific value of the coal [5]. Hence, the fuel quality of IHM coal is superior to OGB in terms of potential energy recovery from thermal conversion. In comparison, the values of *H* are in agreement with values 3.50 – 6.30 wt.% for other coals in literature. However, the *C* was lower than the reported values 62.90 – 86.90 wt.% due to the maturity and rank of the coals examined [18].

Furthermore, the content of pollutant precursor elements; nitrogen (*N*) and sulphur (*S*) of IHM are lower than OGB coal. In comparison, the values were found to be in agreement with typical values of *N* (0.50 – 2.90) wt.% and *S* (0.20 – 9.80) wt.% for coals in the literature [18]. According to *Speight* [19], the presence of *N* and *S* is influential for determining potentially damaging atmospheric emissions resulting from coal energy utilization [19]. This indicates that thermal conversion of IHM coal could potentially result in lower atmospheric gaseous emissions compared to OGB.

The oxygen content of IHM is also lower than OGB. The presence of oxygen in the form of carboxyl, phenolic, or heteroatoms in the coal structure plays an important role in chemical reactivity, rank classification, and potential products from conversion [18, 19]. In comparison, the *O* content for IHM and OGB were higher than reported values (4.40 – 29.90) wt.% in the literature [18]. As stated previously, this may be attributed to the low maturity and rank of the coals. Hence, it can be surmised that IHM and OGB are low-rank coals (LRC).

The proximate analysis of the coals was also determined as presented in Table 1. The results are in good agreement with reported values for MC (0.40 – 20.20) wt.%; AC (5.00 – 48.90); FC (17.90 – 70.40) wt.% except for VM (12.20 – 44.50) wt.% [17]. This is a confirmation of the LRC status of the coal samples based on their high organic volatile matter content. Furthermore, this suggests that the coals will exhibit high reactivity comparable to biomass fuels. Hence, the coals examined in this study are potentially good fuel feedstock for thermal applications.

Lastly, the heating values of the coals are 20.37 MJ/kg for IHM and 16.33 MJ/kg for OGB. The values are in good agreement with the range 16.00 – 34.00 MJ/kg reported for coals [6, 18] and 9.50 – 27 MJ/kg required for coal-fired power plants [5, 20]. Furthermore, the HHVs are below 24 MJ/kg [3] indicating the coals can be categorized as low-rank Lignite (Brown) coal as defined by ASTM D388 [16]. Therefore, the coals can be potentially utilized for coal-fired power generation [3, 19], co-firing with biomass [21], pyrolysis or gasification into energy or chemicals [22, 23].

3.2. Thermal Degradation Characteristics

The thermogravimetric (TG) analysis of IHM and OGB coals was examined from 30 – 900 °C by heating the samples at 10 °C/min under inert atmosphere. The resulting weight loss (TGA) and derivative weight loss (DTG) curves are presented in Figures 1 and 2, respectively. The TG curves exhibit the downward sloping weight loss curves for thermally decomposition coals reported in the literature [24-28]. This indicates temperature significantly influenced the devolatilization of the coal samples under the conditions investigated.

As observed in Figure 1, the thermal decomposition mainly occurred from 30 – 550 °C. However, at temperatures above 550 °C, thermal decomposition plateaued indicating low devolatilization despite the relatively high volatile matter (VM) content. Similarly, Haykiri-Acma and Yaman [14], Sonobe *et. al.,* [21] reported low devolatilization rates for lignite coals under pyrolysis conditions. The observed trends are ascribed to the complete devolatilization of organic VM in the coal samples. In addition, the tailing observed in Figure 1 may be due to low reactivity of the coals resulting fixed carbon and ash content potential coke yield [29, 30] from coal devolatilization.

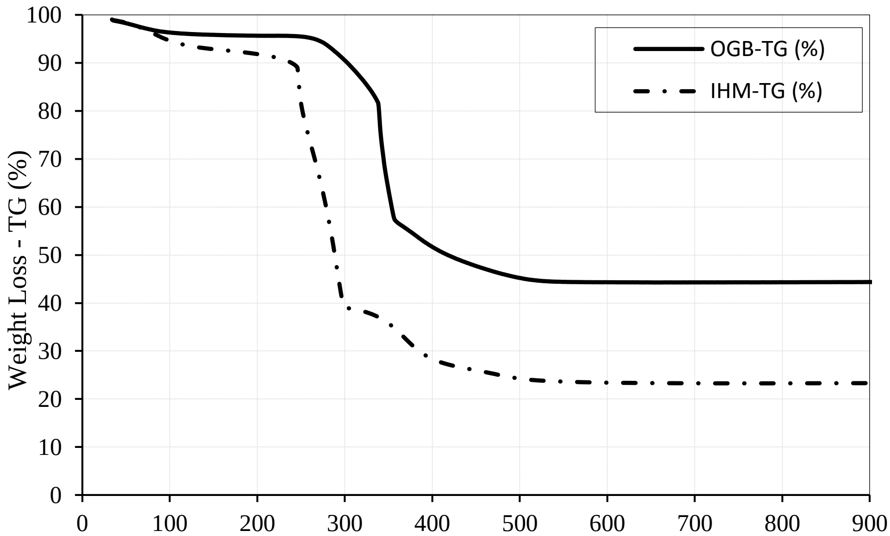

Figure 1. TG Plots for IHM and OGB coals

Likewise, the thermal decomposition behaviour of the coals was examined by derivative weight loss (DTG) analysis as presented in Figure 2. As observed in Figure 2, the DTG curves for IHM revealed three peaks (two symmetric and one asymmetric) during devolatilization. The first was a small symmetric peak from 30 – 150 °C denoting drying or loss of low molecular weight volatiles. The second was a large, sharp, asymmetric tailing peak from 205 – 300 °C denoting the first stage of devolatilization due to loss of organic volatile matter. This reveals the devolatilization of IHM began at 205 °C which is in fairly good agreement with the onset temperature, T_{on} (250 °C) for the lignite decomposition reported by *Sonobe et. al.,* [21].

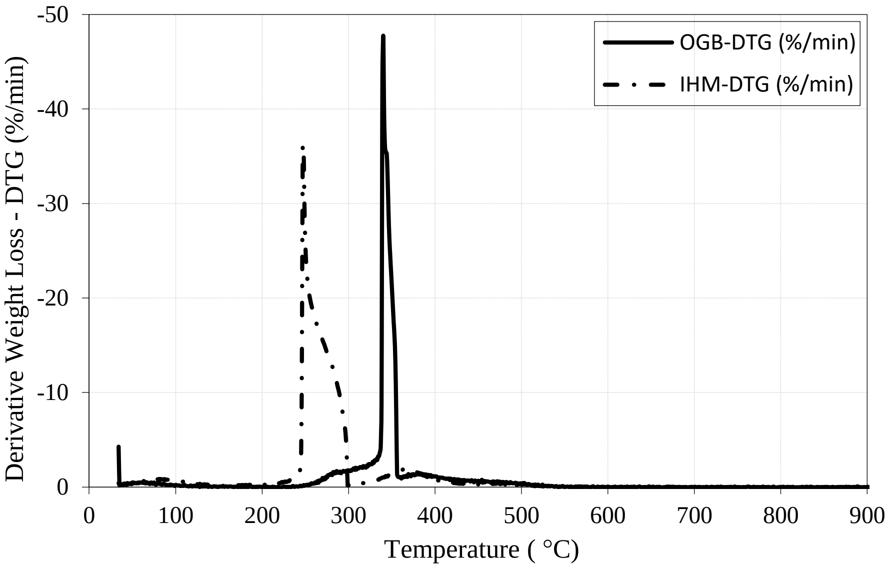

Figure 2. DTG Plots for IHM and OGB coals.

The maximum peak temperature, T_{max} for IHM was at 246.99 °C. The third and last peak was observed from 300 – 550 °C denoting the second stage of devolatilization as characterized by the offset temperature T_{off} of 550 °C. Similar results have been reported for lignite coals in the literature [17, 21]. In contrast, the DTG curves for OGB coal devolatilization revealed two major peaks (one small symmetric and a larger asymmetric peak). The first peak was from 30 – 130 °C denoting drying whereas the second larger peak was from 240 – 530 °C. The second peak can be ascribed to devolatilization or loss of organic volatile matter during TG analysis. Based on this, the onset temperature T_{on} for OGB coal was 240 °C whereas the peak decomposition temperature T_{max} was 340.24 °C and offset temperature T_{off} of 530 °C.

Based on the temperature profile characteristics T_{on}, T_{max} and T_{off}, it can be concluded that IHM is more reactive than OGB. This can be ascribed to the higher content of volatile matter (*VM*), carbon (*C*) and hydrogen (*H*) in IHM compared to OGB coal. Overall, the devolatilization of the coals indicated that thermal decomposition under pyrolysis conditions from 30 – 900 °C resulted in 54.58% weight loss (conversion) for OGB whereas IHM experienced 75.73%. The residual mass, which indicates the coke (char) potential, was 23.30% for IHM and 44.41 % for OGB, respectively, which confirms IHM is more reactive than OGB.

4. Conclusion

The study examined the energy recovery potential of newly discovered Nigerian Lignite (Brown) coals using non-isothermal thermogravimetry under pyrolysis conditions. Therefore, the physicochemical, thermal, and calorific fuel properties of IHM and OGB coals from Nigeria were characterized. The results revealed that IHM and OGB contain satisfactory combustible elements, low moisture, and ash for potential energy recovery from thermochemical conversion. Furthermore, the coal samples displayed sufficiently high heating value (HHV) from 16 – 20 MJ/kg. Based on this, the coals were categorized as Lignite (Brown) coals with potential application in coal-fired power plants or co-firing with biomass. The results for thermal decomposition indicated that coal pyrolysis resulted in 55% weight loss for OGB while IHM experienced 76% which indicates IHM is more reactive than OGB. Based on the fuel properties, the coals were classified as low-rank coals (LRC) with potential application in metallurgical or power generation applications. Overall, the study presents novel data on the physicochemical and thermal fuel properties of the newly discovered Nigerian Lignite coals. This will be vital to the design, optimization, and scale-up of future coal energy recovery applications.

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